Observation of One-Dimensional Second Sound in Superfluid Helium

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A new collective mode of heat transport has been observed in superfluid helium at low temperatures and pressures. Unlike ordinary second sound, this new mode travels at essentially the acoustic-sound velocity and is characterized by the nearly collinear phonon relaxation arising from anomalous dispersion. The mode has been found to persist into the collisionless regime, $\omega\tau > 1$.

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The existence of a propagating temperature wave, second sound, in superfluid ^{4}He was experimentally discovered by Peshkov[1] in 1944. This provided dramatic confirmation of Tisza's and Landau's basic ideas about the superfluid phase of ^{4}He. Landau[2] showed that the ordinary second-sound velocity c_2 could be calculated from macroscopic thermal properties via

$$c_2^2 = \rho_s TS^2/\rho_n C, \tag{1}$$

where ρ_n and ρ_s are the normal and superfluid densities, S and C the entropy and specific heat per unit mass, and T the temperature. Landau[3] later gave a more microscopic description of second sound as a collective density wave in the gas of elementary excitations, the phonons and rotons, comprising the normal component of the fluid. So long as the mean free path of these excitations is short compared to the second-sound wavelength, the mode will propagate with velocity determined by Eq. (1) or, equivalently, derived from the fundamental dispersion relation of the elementary excitations. In the low-temperature, phonon-dominated regime, Eq. (1) reduces to $c_2 = c_0/\sqrt{3}$ with c_0 the ordinary acoustic-sound velocity. Observation[4] of this low-temperature limit for c_2 is very difficult as a result of the rapid decrease of the wide-angle scattering rate $\tau_\perp^{-1}$ required for thermal equilibrium.

It is now well established[5] that at low temperatures and pressures the thermal properties of superfluid helium are dominated by low-energy acoustic phonons which possess anomalous, or upward, dispersion. In this regime the only important scattering process is the three-phonon event and this is, as a result of the small degree of anomalous dispersion, of very small angle. Wide-angle events are very rare, coming largely from multiple small-angle ones and, as a consequence, the propagation of ordinary second sound is inhibited. Maris[6] predicted, however, that in this regime of collinear phonon processes a new, peculiar type of second sound would exist, one in which phonon relaxation occurs only in the direction of propagation. It is the observation of this new collective mode that we report here.

Maris[6] has shown that while true thermal equilibrium obtains only after a time or order $\tau_\perp$, it is possible to have a quasiequilibrium situation after the much shorter time determined by the small-angle collisions. A pseudotemperature[7] can be assigned to groups of phonons propagating in a given direction and equilibrating amongst themselves via small-angle three-phonon events. In this "one-dimensional" situation temperature waves propagate with speeds close to c_0 rather than $c_0/\sqrt{3}$. As a function of frequency ω, calculations show a very gradual rise in the phase velocity from $c_0/\sqrt{3}$ for $\omega << \tau_\perp^{-1}$ to c_0 when $\tau_\perp^{-1} << \omega < \tau_\parallel^{-1}$. It has also been predicted[8] that the mode will persist into the "collisionless" regime $\omega\tau_\parallel > 1$, again because of the reduced dimensionality.

We have employed both cw resonance and pulsed time-of-flight techniques to study this new collective mode. A 3×0.5-mm^2 gold thin-film heater, evaporated on a glass plate, and a novel single-crystal bolometer are arranged in a parallel-plate geometry with superfluid ^{4}He between. The bolometer consists of a GaAs/(AlGa)As heterostructure grown by molecular-beam epitaxy and containing a high-quality two-dimensional electron gas (2DEG). The 2DEG is buried about 1000 Å below the surface of the heterostructure upon which the heat pulses impinge. A magnetic field, typically 5 T, applied perpendicular to the heterostructure surface, biases the 2DEG into the quantum-Hall-effect regime where its electrical conductivity, measured in the Corbino configuration, is higly temperature dependent. Employment of this unconventional detector is an outgrowth of experiments on phonon absorption by the 2DEG in which superfluid helium serves as a spectral filter.[9] For the present experiment, measurements have been performed at temperatures down to 90 mK, and at all pressures below the helium melting point, 25 bars. The spacing between the heater and detector has been determined to be 1.31 mm through measurements of ordinary second sound at temperatures near 1 K. The experimental configuration is depicted in the inset to Fig. 1.

Figure 1 shows the bolometer response following

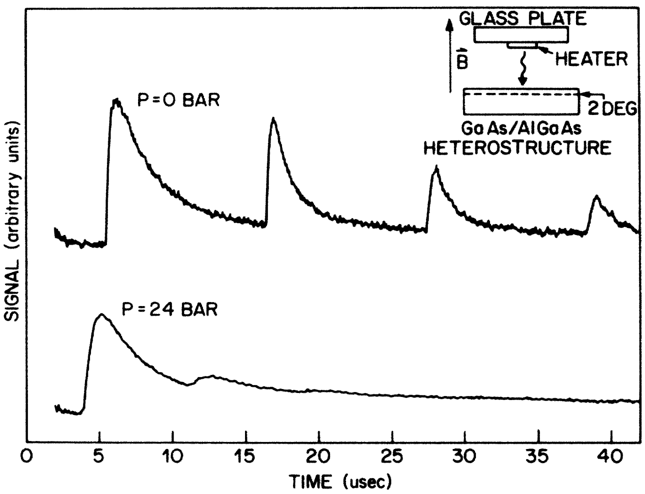

FIG. 1. Heat pulses observed at $T \sim 150$ mK. Note strong train of echoes at low pressure. Inset: Experimental arrangement.

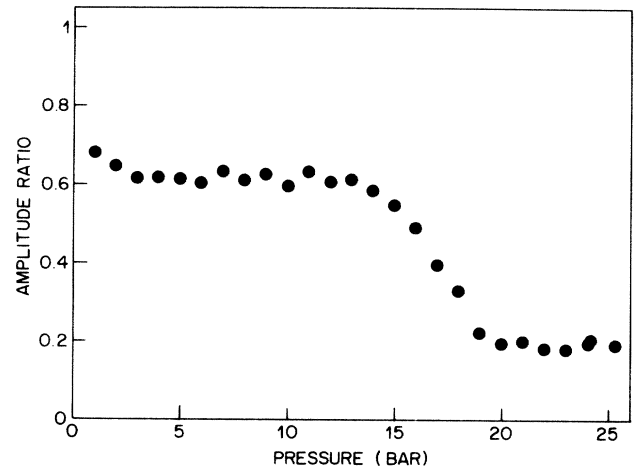

FIG. 2. Ratio of first-echo to main-pulse amplitude vs pressure. Below about 150 mK this ratio is temperature independent.

single heat pulses (typically 10 mW, 100 ns long) at both low and high pressures. At low pressure the leading edge of the first pulse arrives after a delay very close to that expected for either ordinary acoustic sound or for ballistic phonon propagation. Uncharacteristic of ballistic propagation, however, is the long train of large-amplitude sharp echoes, a feature generally associated with a collective mode. For the high-pressure data only one echo is significant and the pulses are reminiscent of ballistic propagation.[4] The time of flight at these pressures gives a speed a few percent less than c_0. In Fig. 2 the ratio of first-echo to main-pulse amplitude is plotted against pressure. Up to about 13 bars this is roughly constant but then falls sharply to a lower plateau reached by 19 to 20 bars. The pulse shapes also exhibit two regimes, with sharp pulse trains at low pressures giving way to broadened single echoes above 20 bars. We interpret this behavior as evidence for "one-dimensional" second sound at low pressures where the phonon dispersion is anomalous, followed by ballistic phonon propagation in the normally dispersive region above 20 bars. While these qualitative features are independent of magnetic field and of the specific GaAs 2DEG structure used, there are variations in the details. For example, the data shown in Fig. 2 depend slightly, but systematically, upon magnetic field through the changing spectral response of the 2DEG detector.

The region of upward dispersion at small phonon wave vector is followed by normal (downward) dispersion and eventually, by the roton minimum. There exists a cutoff energy E_c for phonons below which the three-phonon process limits the mean free path.[10] Above E_c this process is cut off and the mean free path, at low temperature, becomes macroscopically large. A typical heat pulse starts out as a superthermal quasiblackbody distribution of phonons with a characteristic temperature of about 1 K. The three-phonon process rapidly causes down-conversion of those phonons below E_c while those of higher energy progress ballistically. The distribution of the downward-shifted phonons depends upon the propagation distance and is difficult to assess in detail. On the basis of the scattering rate for the three-phonon process one expects essentially no phonons, except those above E_c, to remain above 1 K after traversal of the 1.3 mm to the detector. It is this large mass of low-energy phonons which, self-equilibrating via the nearly collinear three-phonon process, develops into the new collective mode. As the pressure is increased E_c drops smoothly from its zero-pressure value of 9.85 K to zero around 19 or 20 bars above which the phonon dispersion is no longer anomalous.[11] At low pressure, essentially all phonons are participating in the collective mode, but as the pressure is increased an increasing fraction of the phonons are above the cutoff and propagating ballistically. Presumably the very different reflectance for the ballistic phonons and for the collective mode results from the very different wavelengths involved. The collective-mode wavelength is of the order of tens of micrometers as determined from the pulse length (100 ns) and speed of propagation ($c_0 = 238$ m/s at $P = 0$), whereas typical ballistic phonon wavelengths are in the angstrom range.

To prove conclusively that a collective mode with macroscopic wavelength is being detected we have studied the cw response in our parallel-plate "resonator" from dc to 250 kHz at rms power levels in the mi-

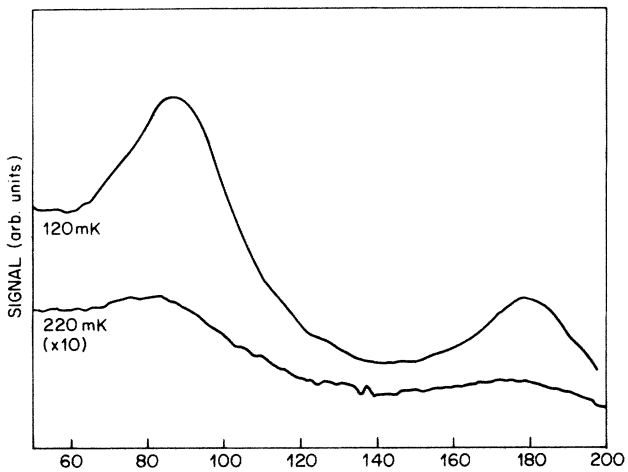

FIG. 3. Standing-wave resonances at saturated vapor pressure. Note the slight frequency shift with temperature.

crowatt range. Aside from the obvious zero-frequency mode associated with temperature oscillations of the entire helium sample, there are as many as three additional resonances, in nearly harmonic sequence, at finite frequencies. Typical frequency spectra, taken at low pressure, of the rms detected signal (at twice the heater excitation frequency) are shown in Fig. 3. We find that these resonances may be calculated, to within a few percent,[12] from the relation

$$f_n = nc_0/2d, \tag{2}$$

where d is the plate spacing. Table I lists the observed frequencies f_1 and f_2, of the two lowest modes at nearly zero applied pressure in a cell with plate spacing of 1.31 mm. Also given are the wave speeds, relative to the acoustic-sound velocity c_0, calculated by use of Eq. (2). As the pressure is increased these modes shift as c_0 does and decrease in amplitude sharply above ~ 15 bars. Above 20 bars the spectrum shows broad gentle oscillations with no obvious normal-mode structure. These resonances are one-dimensional second-sound standing waves, the fundamental and its harmonics, in a parallel-plate geometry.

Using a phonon Boltzmann-equation method Maris[6] has calculated both the speed and the attenuation of second-sound modes as a function of frequency and temperature for superfluid helium at zero pressure. These calculations show a gradual transition from ordinary (phonon) second sound at high temperatures and low frequencies to the one-dimensional mode in the opposite limits. This transition represents the passage of $\omega\tau_\perp$ from $<< 1$ to $>> 1$. The strong decrease of the observed collective-mode signal as the temperature is raised, due to the falling bolometer sensitivity and increasing mode attenuation, limits our measurements to $T < 0.25$ K. Maris' numerical results show the speed of second sound[13] at 100 kHz (near our observed fundamental mode) to rise from $0.95c_0$ to c_0 as the temperature is lowered from 0.25 K. While the data in Table I show a similar dependence, the low Q factor of the modes and the narrow temperature window studied inhibit a detailed comparison. In addition, the observed attenuation is roughly temperature independent below about 0.2 K perhaps signaling the dominance of reflection losses over the bulk attenuation that Maris calculates. The observed Q factor, typically ~ 5, is much smaller than we observe at higher temperatures for ordinary second sound ($Q \sim 80$) in the same cell. We believe that this difference is due to the influence of surface irregularities. Ordinary second sound, which requires large-angle scattering for thermal equilibrium, will not be adversely affected by a random distribution of reflection angles for the individual excitations. The mode observed here, however, equilibrating via small-angle ($< 10°$) three-phonon events, will degrade significantly upon reflection from an irregular surface.

TABLE I. Observed frequencies and wave speeds (Ref. 12) for the two lowest standing-wave resonances at $P = 0$.

	Fundamental			First harmonic		
T (K)	f_1 (kHz)	c_2/c_0	$\omega\tau_\parallel$	f_2 (kHz)	c_2/c_0	$\omega\tau_\parallel$
0.12	89	0.98	1.3	180	0.99	2.6
0.22	85	0.94	0.06	175	0.96	0.12

Further calculations have shown that one-dimensional second sound will continue to propagate into the collisionless limit $\omega\tau_\parallel > 1$. Benin[8] has argued that this is due again to the smallness of the three-phonon scattering angle and he predicts wavelike behavior up to $\omega\tau_\parallel \sim 2700$ at $T = 0.25$ K. With use of Benin's formula[14] for $\tau_\parallel$ and on the assumption that the heat pulse duration of 100 ns defines a sensible "frequency," then $\omega\tau_\parallel \sim 50$ has been observed at 150 mK in the pulsed measurements. The uncertainties inherent in pulsed measurements make this number unreliable and at best a crude estimate. As Table I shows, we have made cw observations at least as high as $\omega\tau_\parallel = 2.6$. For this datum the calculated three-phonon mean free path, $\lambda_\parallel = c_0\tau_\parallel$, is about 40% of the plate spacing. At lower temperatures $\lambda_\parallel$ will exceed the plate spacing and ballistic propagation will take over.

In summary, we have observed a new type of collective mode in superfluid helium at low temperatures and pressures. Both pulsed time-of-flight and cw resonance techniques have been used to study this mode which appears to correspond to the "one-dimensional" second sound predicted by Maris. We have also found the mode to persist into the "collisionless" regime, predicted by Benin to stem from the smallness of the three-phonon collision angle.

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[10]In reality there exists a series of closely spaced cutoffs for phonon decay into two, three, or more phonons. For our purposes we consider only the three-phonon event in which one phonon decays into two. This process has the shortest mean free path and therefore dominates. See L. P. Pitayevskii and Y. B. Levinson, Phys. Rev. B **14**, 263 (1976).

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[12]We estimate the systematic error in determining the plate spacing to be about 2%. The resonant frequency determinations are accurate to about 1% at $T = 0.12$ K and about 2% at $T = 0.22$ K.

[13]At a given temperature the high-frequency limit of the one-dimensional second-sound velocity is actually very slightly higher than c_0. This is due to thermal averaging over the upward phonon dispersion. At 0.25 K Benin (Ref. 8) finds the limiting phase velocity to be $1.015c_0$.

[14]Benin's result (Ref. 8) gives $\tau_{\parallel} = 5.6$ μs at 0.1 K and $P = 0$ and has a T^{-5} temperature dependence.